Polarity-dependent effects of bi-parietal tDCS on the interplay between target location and distractor saliency in visual attention

Magdalena Chechlacz[1,2*], Peter C. Hansen[1]; Joy J. Geng[3], and Dario Cazzoli[4]

[1]School of Psychology, University of Birmingham, Birmingham, B15 2TT, United Kingdom
[2]Department of Experimental Psychology, University of Oxford, Oxford, OX1 3UD, United Kingdom;
[3] Center for Mind and Brain, University of California, Davis, Davis, California 95618, USA; [4] Gerontechnology and Rehabilitation Group, ARTORG Center, University of Bern, 3010 Bern, Switzerland

***Corresponding Author:** Magdalena Chechlacz, School of Psychology, University of Birmingham, Birmingham, B15 2TT, United Kingdom

email: m.chechlacz.1@bham.ac.uk

phone: +44 (0) 121 414 2852

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ABSTRACT

Visual attention allows the allocation of limited neural processing resources to stimuli, based on their behavioural priorities. The selection of task-relevant visual targets entails the processing of multiple competing stimuli, and the suppression of distractors that may be either perceptually salient or perceptually similar to targets. The posterior parietal cortex controls the interaction between top-down (task-driven) and bottom-up (stimulus-driven) processes competing for attentional selection, as well as spatial distribution of attention. Here, we examined whether bi-parietal tDCS would modulate the interaction between top-down and bottom-up processes in visual attention. Visual attention function was assessed with a visual discrimination task, in which a lateralized target was presented alone or together with a contralateral, similar or salient, distractor. The accuracy and reaction times were measured, prior to and during three stimulation sessions (sham, right anodal/left cathodal, left anodal/right cathodal). The analyses demonstrated: (i) polarity dependent effects of tDCS on the accuracy of target discrimination, but only when the target was presented with a similar distractor; (ii) the tDCS-triggered effects on the accuracy of discriminating targets, accompanied by a similar distractor, varied according to the target location; and, (iii) overall, detrimental effects of tDCS on response times were observed, regardless of target location, distractor type and polarity of the stimulation. We conclude that the observed polarity, distractor type and target location dependent effects of bi-parietal tDCS on the accuracy of target detection resulted from both a modulation of the interaction between top-down and bottom-up attentional processes, and the interhemispheric competition mechanisms guiding attentional selection and spatial deployment of attention.

INTRODUCTION

The surrounding environment continuously bombards us with an overwhelming amount of visual information, significantly exceeding our capacity to efficiently analyse it and respond to it. Thus, thriving in a complex visual world depends on the ability to quickly prioritize incoming information. The term visual attention refers to a set of cognitive mechanisms facilitating the allocation of limited neural processing resources, according to the current behavioural goals, and sub-served by specialized frontoparietal neural networks (Corbetta, Kincade, & Shulman, 2002; Corbetta & Shulman, 2002). Visual attention enables the rapid detection of and the response to behaviourally relevant (task-relevant) visual stimuli, while ignoring irrelevant information. In a complex visual scene, this rapid selection of task-relevant visual targets requires the processing of multiple competing stimuli, and also entails the suppression of task-irrelevant stimuli (distractors), which may be either perceptually salient or perceptually similar to the targets (Bundesen, 1990; Corbetta & Shulman, 2002; Duncan, 1980; Duncan & Humphreys, 1989; Geng, 2014; Wolfe, Cave, & Franzel, 1989; Wolfe & Horowitz, 2004; Yantis & Egeth, 1999).

The attentional selection process is commonly studied using various visual search tasks, in which participants are asked to respond to pre-defined targets presented among various distractors (Wolfe, 1998). These visual search tasks do not fully capture the complexity of real-world situations, but enable us to isolate and study essential properties of the real-world visual scenes and attentional selection mechanisms. One implementation of such paradigms, specifically used to explore the interplay between top-down and bottom-up processes in attentional selection, employs a direct competition between perceptual saliency and task relevance (e.g., Geng & Diquattro, 2010; Geng & Mangun, 2011; Mazaheri, DiQuattro, Bengson, & Geng, 2011; Theeuwes, 1992; Zehetleitner, Koch, Goschy, & Muller, 2013). On the basis of the findings derived from the behavioural performance in such paradigms, it has been suggested that the initial capture of attention is stimulus-driven (i.e., bottom-up, determined by stimuli saliency), and that a top-down,

goal directed selection only occurs later in time (for review see Theeuwes, 2010). While it is debatable whether the capture of attention is predominantly stimulus-driven, it has been repeatedly shown that there is always some combination of bottom-up and top-down influences that determines the deployment of visual attention (for review see Corbetta & Shulman, 2002; Theeuwes, 2010; Yantis, 2000; Yantis, 2002). Furthermore, the results of prior studies strongly indicate that top-down and bottom-up attentional processes exert a mutual and flexible modulation on each other. Specifically, the attentional capture exerted by a salient distractor (i.e., a known non-target) can also guide the subsequent deployment of top-down attention, and thus facilitate target detection (DiQuattro & Geng, 2011; Geng & Diquattro, 2010).

In the human brain, visual attention is controlled by several interconnected cortical areas, which are organized into two functionally specialized frontoparietal networks (Corbetta & Shulman, 2002). It is generally thought that the dorsal network controls the ability to orient attention in space, while the ventral network is predominantly involved in target detection and attentional reorienting to salient, but unexpected stimuli. However, this strict dorsal-ventral dichotomy has been frequently questioned, and it has been also suggested that the two system are not entirely independent (for review see Singh-Curry & Husain, 2009; Shomstein, 2012). The key cortical region, functionally engaged in visual attention, is the posterior parietal cortex (PPC). This large and highly specialized cortical area is thought to control both the interaction between top-down (task-driven) and bottom-up (stimulus-driven) processes competing for attentional selection, as well as the spatial distribution of visual attention. In fact, the aforementioned models of networks sub-serving visual attention incorporate the PPC into both the dorsal and the ventral systems. This is based on the evidence from functional neuroimaging studies as well as from neuropsychological data (from patients with attentional deficits) suggesting, that distinct PPC sub-regions control discrete attentional processes (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Corbetta & Shulman, 2002, 2011). Specifically, the PPC sub-region along the intraparietal sulcus (including both the

inferior and the superior parietal lobule) controls the voluntary orienting of attention to given spatial locations, and is involved in top-down attentional control, while a more ventral PPC sub-region along the temporoparietal junction (TPJ) is necessary for reorienting attention to unattended/unexpected visual targets and is involved in bottom-up attentional control (Corbetta et al., 1998; Corbetta et al., 2000; Corbetta et al., 2002; Corbetta & Shulman, 1998, 2002; Doricchi, Macci, Silvetti, & Macaluso, 2010; Friedrich, Egly, Rafal, & Beck, 1998; Mesulam, 1981; Mevorach, Hodsoll, Allen, Shalev, & Humphreys, 2010; Nobre et al., 1997; Posner, Walker, Friedrich, & Rafal, 1984; Shulman et al., 2010; Vandenberghe et al., 1996). Although clear evidence for a functional specialization within the PPC sub-regions exists, several functional neuroimaging studies and investigations in neurological patients also suggest that these two attention systems strongly interact with each other, enabling a dynamic and flexible control of attention in both top-down and bottom-up fashion (for review see Shomstein, 2012; Vossel, Geng & Fink, 2014). Finally, while the PPC is traditionally associated with the control of attention, this region is also involved in a range of other cognitive functions, including learning, memory, decision-making, planning, and reward (for review see Constantinidis, Bucci, & Rugg, 2013).

The attention networks are functionally lateralized (i.e., the allocation of attention to the left versus right visual field is controlled by the respective contralateral hemisphere), as well as asymmetrically organized, with a right hemispheric dominance. Relevant evidence, supporting the functional lateralization and right hemispheric dominance in spatial attention, comes from pseudoneglect in healthy participants and from neurological patients with visual attention disorders, such as neglect and extinction (Bowers & Heilman, 1980; Corbetta & Shulman, 2011; Driver & Mattingley, 1998; Halligan, Fink, Marshall, & Vallar, 2003; Heilman & Valenstein, 1979; Jewell & McCourt, 2000; McCourt & Jewell, 1999; Vallar, 1998). In addition to evidence for the lateralization of spatial attention, there appears to be also evidence for a hemispheric asymmetry in attentional processing of salient stimuli. For example, based on behavioural findings in brain-damaged patients and on

experimental manipulations using transcranial magnetic stimulation, Mevorach and colleagues demonstrated a specific involvement of the left parietal cortex in the attentional suppression of salient, but task-irrelevant, information (Mevorach et al., 2006a,b; Mevorach et al., 2009).

Transcranial direct-current stimulation (tDCS) has been shown to modulate performance in various behavioural tasks, by affecting the excitability of cortical areas sub-serving the corresponding cognitive processes. In particular, it has been shown that the anodal stimulation increases, while the cathodal stimulation decreases cortical excitability and thus tDCS allows to trigger differential outcomes in a polarity-dependent manner (Nitsche et al., 2008; Nitsche & Paulus, 2000, 2001). Furthermore, it has been demonstrated that the effects triggered by tDCS may persist for up to few hours after the delivery of stimulation, and that these effects strongly depend on the stimulation parameters, i.e., the intensity, duration and timing of the stimulation with respect to the administered behavioural task (Miranda, Faria, & Hallett, 2009; Moos, Vossel, Weidner, Sparing, & Fink, 2012; Pirulli, Fertonani, & Miniussi, 2013; Sparing & Mottaghy, 2008; Sparing et al., 2009; Teo, Hoy, Daskalakis, & Fitzgerald, 2011). Numerous prior studies have indicated that tDCS applied over the PPC can modulate visuospatial attention. However, the reported effects seem to be somewhat inconsistent and also to be highly dependent on the stimulation parameters employed by different studies, in particular the stimulation site (i.e., left versus right PPC) and polarity (e.g., Benwell, Learmonth, Miniussi, Harvey, & Thut, 2015; Bolognini, Fregni, Casati, Olgiati, & Vallar, 2010; Filmer, Dux, & Mattingley, 2015; Giglia et al., 2011; Moos et al., 2012; Roy, Sparing, Fink, & Hesse, 2015; Sparing et al., 2009; Weiss & Lavidor, 2012; Wright & Krekelberg, 2014). For example, Moos et al (Moos et al., 2012) have shown that tDCS applied over the right PPC can modulate the top-down control of attention, but a facilitatory effect was only observed after cathodal, but not anodal, stimulation, and only with a current strength of 2mA (but not 1mA). Furthermore, Roy et al (Roy et al., 2015) have reported strongly lateralized effects (as measured by efficiency of target detection in the left versus right visual field) after anodal tDCS was applied over the right but not the left PPC.

These results support two previously proposed accounts of the asymmetrical organization of visual attention and right-hemispheric dominance i.e., the notion of a differential involvement of the two hemispheres in attentional control (Heilman & Van Den Abell, 1980) and the Kinsbourne's interhemispheric rivalry model (Kinsbourne, 1987, 1993).

Overall, the results of several prior studies indicate that tDCS applied over the PPC can be used to modulate both spatial and non-spatial aspects of visual attention, including detection of lateralized targets, spatial re-orienting, top-down control of attention and attentional capacity (e.g., Benwell et al., 2015; Bolognini et al., 2010; Filmer et al., 2015; Giglia et al., 2011; Moos et al., 2012; Roy et al., 2015; Sparing et al., 2009; Weiss & Lavidor, 2012; Wright & Krekelberg, 2014). However, it should be noted that the spatial focality of tDCS, when applied using conventional rectangular or square electrodes (standard size 7x5 or 5x5 cm; as in the studies cited above) does not allow to precisely target distinct sub-regions within the PPC, or to dissociate specific, differential influences on the dorsal and ventral attention systems.

In the current study, we examined whether and how bi-parietal tDCS (over the left and the right PPC) would modulate the interaction between top-down and bottom-up processes in visual attention. We opted for a bi-parietal tDCS stimulation approach in order to differentially modulate the activity of the left and the right PPC and to alter inter-hemispheric dynamics by simultaneously inhibiting one side and exciting the other. This would not be possible with the more commonly used unilateral tDCS stimulation approach. We assessed the effects of stimulation by means of a simple visual discrimination task, in which a lateralized (left or right visual hemi-field) target was presented alone or together with a similar or salient distractor (appearing in the opposite hemi-field). The two tDCS electrodes, with opposite polarities, were applied over the PPC of either hemisphere (i.e., anode on the right PPC and cathode on the left PPC, or vice versa), in order to differentially modulate the activity of these regions. This allowed us to examine whether shifting the inter-hemispheric balance between the posterior parietal regions of the two hemispheres would: (i) have

an impact on the functional lateralization of visual attention (left-right asymmetry in the target detection), and/or (ii) modulate the effect of distractor saliency on target detection. Furthermore, the bi-parietal approach enabled us to examine whether right/left hemispheric asymmetry has any influence on the interplay between top-down and bottom-up processes in visual attention.

As the target and the distractor were simultaneously presented within the opposite visual hemi-fields, we hypothesized that we would find an opposite influence of stimulation with reverse polarity (i.e., right anodal/left cathodal versus left anodal/right cathodal tDCS) on the effects exerted by the two types of distractors (i.e., either the perceptually salient or the perceptually similar distractors or both) on target detection. Moreover, taking into account hemispheric asymmetries in visual attention, we anticipated potential differential effects of stimulation with reverse polarity on the detection of left versus right targets.

MATERIAL AND METHODS

Participants. Twenty-one healthy volunteers (10 men; mean ± SD age = 25.8 ± 5.3) took part in the study, which consisted of three separate brain stimulation sessions. Exclusion criteria included any previous history of neurological or psychiatric disorders, and any contraindication to transcranial direct current stimulation (Poreisz, Boros, Antal, & Paulus, 2007). Both left- and right-handed participants were recruited for the study, and hand dominance was assessed by means of the Edinburgh handedness inventory (Oldfield, 1971). All participants had either normal or corrected-to-normal vision. All study participants provided written informed consent, in compliance with the relevant protocols approved by the University of Oxford Central University Research Ethics Committee. All experimental procedures were conducted in accordance with the latest version of the Declaration of Helsinki.

Study Design and Procedure. The study consisted of three experimental sessions, each entailing a different type of transcranial direct current stimulation (tDCS), separated by at least one week. Each experimental session included a short practise version of the task, the full versions of the

visual discrimination task (see Experimental Task section) performed without stimulation (as a baseline), followed by the repetition of the full experimental task performed during the tDCS application. tDCS was administered by means of a battery-powered, constant current stimulation device (neuroConn DC-STIMULATOR, GmbH, Illmenau, Germany), using 5x5 cm rubber electrodes placed in saline soaked sponges. The saline was used to minimize the risk of skin irritation and to reduce impedance. The elastic strap was used to secure electrodes in place and to ensure a good contact with the scalp. 1.5mA tDCS was applied bilaterally over the left and the right PPC, the placement of the electrodes being determined according to the 10-20 EEG system (P3 and P4, respectively; Jasper, 1958). Each of the three sessions included a different stimulation condition: (i) RH anodal/LH cathodal, i.e., right PPC anodal and left PPC cathodal tDCS stimulation lasting 1200 s (20 minutes); (ii) LH anodal/RH cathodal, i.e., left PPC anodal and right PPC cathodal tDCS stimulation lasting 1200 s; and, (iii) sham stimulation. Sham stimulation consisted of an initial 30s of real left PPC cathodal and right PPC anodal tDCS stimulation (applied in order to induce the itching/tingling sensation on the scalp under the electrodes, which is occasionally experienced by participants at the beginning of tDCS application), and of a subsequent automatic switching off of the device. Both the 1200s and 30s tDCS stimulation was flanked by a gradual 15s upwards and 15s downwards current ramp. The order of the three stimulation sessions was randomised across participants and the study was conducted in a single-blind fashion i.e., only the experimenter but not the participant knew which stimulation type was delivered during each session. The start of the experimental task was always triggered 3 minutes after the onset of either the sham or the real tDCS stimulation. This ensured that, for the experimental sessions entailing real tDCS, the stimulation lasted for the whole duration of the task.

Experimental Task. Participants were assessed on a visual discrimination task (a modified version of a previously published task, see Geng & Diquattro, 2010), in which a lateralized target, presented either within the left or the right visual field, appeared alone or together with a contralateral

distractor. Each trial began with a central black fixation cross presented for an interval randomly varying between 1500-2000ms, and followed by a visual display. The visual display consisted of either one (target alone) or two (target plus distractor) “t-like” stimuli (see Fig. 1), presented for 150ms and subsequently masked for 500ms. The target was present on every trial, and the distractor, if present, always appeared simultaneously with the target. The fixation cross remained visible during the whole visual display duration, and the next trial began only after the participant responded. In each visual display, the target was presented randomly within the left or the right visual field, on the horizontal meridian of the screen. The target was either an upright or an inverted ” † “. The distractors were 90° rotations of the target stimuli. The distractor was randomly selected, and equally likely to be rotated clockwise or counter-clockwise when presented with either the left or the right target. The targets were always low contrast (Michelson Contrast Ratio=0.51; foreground luminance 5.4 cd/m^2; background luminance 16.8 cd/m^2). The distractors were either low contrast like the targets i.e., similar distractors (Michelson Contrast Ratio=0.51; foreground luminance 5.4 cd/m^2; background luminance 16.8 cd/m^2) or high contrast i.e., salient distractors (Michelson Contrast Ratio=0.96; foreground luminance 0.54 cd/m^2; background luminance 30.5 cd/m^2). The subsequent mask was created from scrambled stimuli (see Fig. 1). The black fixation cross and the stimuli were presented on a grey background (9.8 cd/m^2). The three main types of stimulus display were: target alone, target plus salient distractor and target plus similar distractor (see Fig. 1). The target was equally likely to be presented in the upright or inverted position, to appear in the left or the right visual hemi-field, as well as equally likely to appear either alone or together with a contralateral similar or contralateral salient distractor. Both targets and distractors were 1.4x1.4° in size, and were presented at 7.3° eccentricity to the left or to the right of the central fixation cross.There was a total of 432 trials in the experimental task, and 36 trials in the practise task. Participants were instructed to maintain central fixation and to respond, as quickly and as accurately as possible, to the target orientation on each trial (i.e., upright

or inverted ” † “), by pressing the upward or downward arrow keys on a computer keyboard, respectively. Both the reaction times (RT) and the accuracy data were recorded for each trial, and entered into data analysis.

Data analysis. For the purpose of the data analysis, we calculated mean accuracy and mean RT (for correct trials only), separately for each main task condition (type of stimulus display), and target location (i.e., left target alone, right target alone, left target with salient distractor, right target with salient distractor, left target with similar distractor and right target with similar distractor). The same calculations were applied to the experimental task data collected prior and during each stimulation session. To evaluate the overall performance on the visual discrimination task, we combined (averaged) all the baseline datasets from each participant (i.e., experimental task performed prior to stimulation), separately for reaction time (RT) and accuracy measures. The merged data were then entered into a 2x3 repeated measures ANOVA, with the within-subjects factors defined as the target location (left hemi-field, right hemi-field) and the distractor type (salient distractor, similar distractor, no distractor). In order to account for any inter-session variability in performance, prior to the analyses of the effects of stimulation, we normalized data across stimulation conditions. This was done by creating an index of performance change, defined by subtracting (RT and accuracy) baseline performance (i.e., before the application of the stimulation within the same testing session) from performance measured during stimulation, separately for each session i.e., RH anodal/LH cathodal, LH anodal/RH cathodal and sham. Positive values indicate higher accuracy and longer RTs during stimulation compared to baseline; and negative numbers indicate lower accuracy and shorter RTs (faster performance) during stimulation than baseline. These calculated scores were entered into a 3x3x2 repeated-measures analysis of variance (ANOVA), with the within-subjects factors defined by the stimulation type (RH anodal and LH cathodal, LH anodal and RH cathodal, sham stimulation), the distractor type (salient distractor, similar distractor, no distractor) and the target location (left hemi-field, right hemi-field). The

statistical analyses were performed separately for accuracy and RT data using SPSS 21 (IBM SPSS Statistics, NY, USA). All subsequent pairwise post-hoc tests were performed using Statistica 6.0 (StatSoft Inc., OK, USA), applying the Bonferroni correction.

The two key ANOVA analyses (i.e., examining the effects of the different stimulation conditions on the accuracy and RTs of target detection) were supplemented by a Bayesian inference approach, which allows to quantify the strength of the evidence from the data in support of the observed effects of the active stimulation (Wetzels et al., 2011 Wagenmakers et al., 2017a). We only employed the additional Bayesian statistics for these two key analyses in order to avoid unnecessary lengthening of the paper. Bayesian paired samples t-tests (Rouder, Speckman, Sun, Morey, & Iverson, 2009) were conducted using an open source statistical software JASP (JASP version 0.8.1.2, JASP Team 2017; Wagenmakers et al., 2017b). For all reported Bayesian t-tests, we used a default prior on the effect size for the alternative hypothesis, with Cauchy distribution centered on zero, with scale parameter r=0.707. We reported Bayes factors (BF_{10}) in favour of the alternative hypothesis, expressing the probability of the data given H1 relative to H0 (i.e., values larger than 1 are in favour of H1). The Bayes factors (BF_{10}) were subsequently interpreted in accordance to Jeffreys (Jeffreys, 1961) and Wetzels et al. (Wetzels et al., 2011). Additionally, we performed robustness checks by re-calculating the Bayes factors across a wide range of priors i.e., by varying the scale parameter r (range 0 to 1.5). All the conducted checks confirmed that the reported Bayes factors were robust and not influenced by prior choice.

RESULTS

Baseline. In agreement with prior reports (DiQuattro & Geng, 2011; Geng & Diquattro, 2010), the repeated measures ANOVAs showed that accuracy was significantly higher and RTs were significantly shorter, in the salient distractor condition and in the no distractor condition, compared to the similar distractor condition (Fig. 2AB; a significant main effect of distractor type on

performance accuracy $F(2,40) = 35.7$, $p<0.0001$; partial $\eta^2=0.641$, and on RTs $F(2,40) = 43.6$, $p<0.0001$; partial $\eta^2=0.685$).

In addition to main effect of distractor type on the performance accuracy ($F(2,40) = 35.7$, $p<0.0001$; partial $\eta^2=0.641$), we also found a significant main effect of target location ($F(1,20) = 8.8$, $p<0.001$; partial $\eta^2=0.305$) and a significant interaction between target location and distractor type ($F(2,40) = 9.8$, $p<0.0001$; partial $\eta^2=0.328$; Fig. 2A). Subsequent pairwise post-hoc tests revealed that this interaction was mainly attributable to a significant effect of distractor type on targets located on the left (all p values <0.001; Fig. 2A). For the target located on the right participants were more accurate only on trials with no distractor compared to trials with similar distractors ($p<0.01$; other p values >0.1). Furthermore, accuracy was significantly lower for targets located on the left compared to targets located on the right in the presence of a distractor ($p<0.0005$), but not when the targets were presented alone ($p>0.1$).

The subsequent RT analysis revealed significant main effects of both distractor type ($F(2,40) = 43.6$, $p<0.0001$; partial $\eta^2=0.685$) and target location ($F(1,20) = 12.9$, $p<0.005$; partial $\eta^2=0.393$), but in contrast to the accuracy data, there was no significant interaction between target location and distractor type (Fig. 2B). As indicated by subsequent post-hoc tests, participants were significantly slower on trials in which targets were presented with similar distractors compared to trials with salient distractors or no distractors ($p<0.0005$). However, there was no significant difference between trials with salient distractors and trials with no distractors ($p>0.5$).

To test for differences in baseline performance between the three separate experimental sessions and for a potential effect of session order on RTs and accuracy (the order of the three experimental sessions was randomised across participants), we performed a mixed-model repeated measures ANOVA with session type (baseline testing prior to the three types of stimulation: RH anodal/LH cathodal, LH anodal/RH cathodal, sham), distractor type, and target location as within-subject factors, and session order as a between-subject factor. Both RT and accuracy data showed neither

an effect of session (no significant difference in the baseline performance, i.e., prior to application of the stimulation, between the three sessions), nor an effect of session order. Furthermore, no significant interactions between either target location or distractor type with session order were observed (all p values >0.1). However, we found a significant interaction between session type and distractor type ($F(4,56) = 2.52$, $p=0.05$; partial $\eta^2=0.144$) when analyzing RT data. No other interactions with session type were significant (all p values >0.1). Post-hoc tests revealed that the significant interaction was driven by a baseline difference between trials with salient distractors and trials with no distractors in one of the three sessions, i.e., RH anodal/LH cathodal ($p<0.05$). In all baseline sessions (RH anodal/LH cathodal, LH anodal/RH cathodal, sham) participants were significantly slower on trials in which targets were presented with similar distractors compared to trials with salient distractors or no distractors ($p<0.0001$). However, on trials with salient distractors compared to trials with no distractors, this difference was only significant in case of RH anodal/LH cathodal session ($p<0.05$).

tDCS effects. The examination of the accuracy data suggested a polarity dependent (polarity specific) effect of the bi-parietal stimulation (Fig. 3). Specifically, a repeated measures ANOVA showed a significant main effect of stimulation type ($F(2,40) = 7.1$, $p<0.005$; partial $\eta^2=0.262$) and a significant interaction between stimulation type and distractor type ($F(4,80) = 5.95$, $p<0.0001$; partial $\eta^2=0.229$). Furthermore, a significant three-way interaction between stimulation type, target location, and distractor type was observed ($F(4,80) = 2.7$, $p<0.05$; partial $\eta^2=0.119$), indicating that the relationship between stimulation type and distractor saliency differed depending on the target location. Post-hoc analyses showed that the bi-parietal stimulation only affected detection of targets located on the left ($p<0.0001$) but not on the right ($p>0.1$; Fig. 3AB). The post-hoc tests demonstrated that LH anodal/RH cathodal stimulation (as compared to sham) decreased accuracy detection of left targets presented with similar distractors ($p<0.0001$) but not of left targets presented either with salient distractors or alone ($p>0.1$). The post-hoc analyses indicated

significant polarity specific (polarity dependent) effects of stimulation on the accuracy. Specifically, the LH anodal/RH cathodal stimulation significantly decreased the accuracy of left targets presented with similar distractors as opposed to not only the sham condition but also the RH anodal/LH cathodal stimulation ($p<0.0001$; Fig. 3A). Moreover, the stimulation effects on the detection of left targets accompanied by perceptually similar distractors tended to be opposite for the two active tDCS conditions (i.e., LH anodal/RH cathodal and RH anodal/LH cathodal stimulation). However, it should be noted that only the LH anodal/RH cathodal stimulation significantly decreased accuracy, while the improvement in accuracy following the RH anodal/LH cathodal stimulation did not reach statistical significance, as compared to sham condition (Fig. 3A).

In agreement with the above post-hoc analyses, the Bayesian paired t-tests, comparing the effects of sham versus LH anodal/RH cathodal versus RH anodal/LH cathodal stimulation on the detection of either left or right targets accompanied by salient and similar distractors (Table 1), demonstrated very strong evidence in favour of the alternative hypothesis. These tests indicated significant polarity specific effects of stimulation on the accuracy, namely that LH anodal/RH cathodal stimulation as compared to both sham (BF_{10}=86.249) and RH anodal/LH cathodal (BF_{10}=100.208) stimulation, substantially decreased accuracy detection of left targets presented with similar distractors[1]. By contrast to "classic" inferential analysis (as above), using Bayesian statistics we also found moderate evidence in favour of a difference between LH anodal/RH cathodal versus RH anodal/LH cathodal stimulation on the detection of left targets accompanied by salient distractors (BF_{10}=5.398). The above results might be suggestive of the two active stimulation conditions producing opposite effects (Fig. 3A) on the detection of left targets. However, the notion of the opposite effects (LH anodal/RH cathodal versus RH anodal/LH cathodal) should be interpreted with

[1] We have also performed additional Bayesian paired samples t-test comparing the effects of LH anodal/RH cathodal stimulation versus the RH anodal/LH cathodal stimulation using sham normalized score to index the effects of active tDCS (tDCS-sham/tDCS+sham) i.e., controlling for the change induced by sham stimulation. Again, this analysis provided a very strong evidence in favour of the alternative hypothesis (BF_{10}=103.575), i.e., that the effects of the two type of active stimulation conditions (LH anodal/RH cathodal and RH anodal/LH cathodal) on detection of left targets presented with similar distractors, were indeed different.

caution as the comparisons of the effects of RH anodal/LH cathodal stimulation versus sham provided only anecdotal (very weak) evidence in the support of alternative hypothesis (BF_{10}=0.345 for left targets presented with similar distractors; BF_{10}=0.496 for left targets presented with salient distractors). All other comparisons provided either weak evidence in favour of the alternative hypothesis (BF_{10}>1/3 and <3) or moderate evidence in favour of the null hypothesis (BF_{10} < 1/3).[2]

Finally, to test whether there was a link between session order and the observed effects of stimulation type on accuracy measures, we repeated our analysis using a mixed-model repeated measures ANOVA with the session order as a between-subject factor, and with the stimulation type, distractor type and target locations as within-subject factors. We found neither a significant effect of session order, nor any significant interactions with this factor (all p values >0.1).

The subsequent analysis of the effects of stimulation on response times (RTs; correct trials only) suggested a detrimental effect of bi-parietal tDCS stimulation, regardless of its polarity. Overall participants responded faster when performing the task for the second time during each session (i.e., task performance during stimulation, both real and sham, as compared to baseline performance), with the faster RTs being observed for all types of stimulus display i.e., regardless of both stimulation type and target location. Nevertheless, this decrease in RTs was significantly smaller when real tDCS was applied (irrespectively of its polarity) as compared to the sham condition (Fig. 4; please note that larger negative values plotted on Fig. 4, indicate the faster performance during the second session compared to baseline).

While a repeated measures ANOVA showed no main effect of stimulation, we found a significant interaction between stimulation type and distractor type ($F(4,80) = 2.5$, $p<0.05$; partial $\eta^2=0.112$). The pairwise post-hoc tests demonstrated that this interaction was driven by: (i) the LH anodal/RH cathodal stimulation having a significant detrimental effect on the decrease in RTs as compared to

[2] Thus overall, the 'classical' (ANOVA followed by post-hoc tests) and Bayesian statistics converged, indicating the robustness of our conclusions about polarity dependent effects of tDCS on the accuracy of target discrimination, but only when the target was presented in the left hemi-field and with a similar distractor.

sham in all distractor type conditions, and (ii) the RH anodal/LH cathodal stimulation having a significant detrimental effect on the decrease in RT compared to sham condition only when the target was presented with a similar distractor (Fig. 4 depicts the significant post-hoc pairwise comparisons after Bonferroni correction). Interestingly, interference effects on RT by LH anodal/ RH cathodal stimulation was present in all distractor conditions and target locations; this differed from the more specific effects that LH anodal/ RH cathodal stimulation had on accuracy. Similarly, while RH anodal/ LH cathodal stimulation only interfered with RT when the distractor was similar, there were no effects of target location. Together these results indicate that the effects of tDCS stimulation on RTs are more general across conditions than on accuracy.

In agreement with the above post-hoc analyses, the Bayesian paired t-tests, comparing the effects of sham versus LH anodal/RH cathodal versus RH anodal/LH cathodal stimulation on the RTs (Table 2), demonstrated moderate evidence in favour of the alternative hypothesis, namely that the LH anodal/RH cathodal stimulation had a significant detrimental effect on the decrease in RTs as compared to sham condition, regardless of the distractor type (salient distractor BF_{10}=5.173; similar distractor BF_{10}=4.223; no distractor BF_{10}=3.942). Furthermore, the Bayesian analysis provided weak evidence (BF_{10}>1/3 and <3) that RH anodal/LH cathodal stimulation had a significant detrimental effect on the decrease in RT compared to sham stimulation, when the target was presented with a similar distractor (BF_{10}=1.449). All other comparisons provided negligible evidence in support of alternative hypothesis or moderate evidence in favour of the null hypothesis.

Finally, to test for a potential effect of session order on the impact of stimulation on RTs, we repeated our analysis using a mixed-model repeated measures ANOVA with the session order as a between-subject factor, and as before, with the stimulation type, distractor type, and target locations as within-subject factors. We found neither an effect of session order and nor any significant interactions with the latter (all p values >0.1).

DISCUSSION

In the present study, we employed bi-parietal tDCS to modulate the interaction between top-down and bottom-up processes in visual attention, as assessed by a visual target discrimination task, in which a lateralized (to either the left or the right visual hemi-field) target was presented alone or together with a contralateral similar or salient distractor. In addition to examining whether the bi-parietal stimulation would modulate the effect of saliency of the contralateral distractor on the detection of target (e.g., DiQuattro & Geng, 2011; Geng & Diquattro, 2010; Hickey, McDonald, & Theeuwes, 2006; Jewell & McCourt, 2000; Leblanc, Prime, & Jolicoeur, 2008; Proulx & Egeth, 2006, 2008; Theeuwes, 2010), we also aimed to explore whether shifting the inter-hemispheric balance between the posterior parietal regions of the two hemispheres would have an impact on the functional lateralization of visual attention (i.e., left-right asymmetry in the target detection; see Heilman & Van Den Abell, 1980; Jewell & McCourt, 2000; Kinsbourne, 1987, 1993; Mesulam, 1981; Nicholls, Bradshaw, & Mattingley, 1999). On the whole, the results showed: (i) polarity dependent effects of tDCS stimulation on the accuracy of target discrimination but only when the target was presented with a perceptually similar distractor, and (ii) overall detrimental effects of tDCS on RTs, regardless of stimulation polarity. Interestingly, we not only found that the tDCS affected the accuracy of target detection in polarity-dependent manner, but also that these effects varied according to the target location and distractor type. By contrast, the effects of the tDCS on RTs of target detection were influenced by neither the stimulation polarity nor the target location nor distractor type. This suggests that the effect of tDCS on accuracy was highly specific and only affected the most difficult condition in which the target was paired with a similar distractor and the target was contralateral to the hemisphere undergoing cathodal stimulation. In contrast, the effect of RT appeared to be more general, affecting performance across conditions irrespective of attentional competition.

For the purpose of the current study we employed a modified version of the task (shorter presentation of visual display and visual masking), which was previously used to demonstrate, based on the analysis of behavioural performance and eye-tracking data, that a strong attentional bottom-up capture exerted by a salient distractor ("known non-target") guides the deployment of top-down attention, and thus assists target detection (DiQuattro & Geng, 2011; Geng & Diquattro, 2010). Specifically, prior experiments conducted by Geng and DiQuattro (Geng & Diquattro, 2010) indicated that, while the first saccade was more likely to be directed towards a salient object (despite prior knowledge that only a distractor but not a target could be salient), the salient distractor seemed to facilitate rather than interfere with target detection (see also Hickey et al., 2006; Leblanc et al., 2008; Proulx & Egeth, 2006, 2008) for further arguments in relation to the effects of non-target/distractor saliency on target detection). Furthermore, eye-tracking data showed that this facilitation was driven by two strategies: (i) inhibition when the first saccade was directed towards a target (fewer additional saccades to salient non-target once the target was detected), and (ii) rapid rejection when the first saccade was captured by a salient distractor (Geng & Diquattro, 2010). In agreement with these prior studies (DiQuattro & Geng, 2011; Geng & Diquattro, 2010), our baseline behavioural data indicated that a perceptually salient distractor facilitated, while a similar distractor hampered, target detection. While in the current study we did not employ eye-tracking (and thus we were unable to distinguish the time course of attentional competition between targets and distractors), our data does seem to support the idea that while the similar distractor hampers target discrimination, the rapid rejection of salient distractor provides information allowing to quickly reorient attention towards the target and thus facilitate target discrimination (upright or inverted "†"). These findings are also consistent with the assumption that the initial capture of visual attention can be stimulus-driven (i.e., bottom-up, determined by stimuli saliency), with the top-down, goal directed selection occurring later in time (for review see Theeuwes, 2010). It should be also noted that the lack of eye-tracking impeded the

ability to: (1) distinguish between trials with first saccade directed towards distractor versus trials with first saccade directed towards target, and (2) measure if the fist saccade was directed towards the left- versus the right hemi-field. Although this is a potential limitation of the current study (i.e., eye-tracking could have aided the interpretation of the results), the observed effects were robust against the more subtle effects of attentional competition that can be teased out with eye-tracking. We also show (baseline data) that the effect of distractor type on the accuracy but not the RTs of targets detection varied depending on target location. Specifically, the accuracy was significantly lower for targets located on the left compared to the right targets. But this "striking lateralization" was only observed in the presence of contralateral either salient or similar distractor but not when targets were presented alone. This finding is difficult to explain in terms of the left spatial bias in the allocation of visual attention resulting from the right hemispheric dominance (pseudoneglect; see for example Jewell & McCourt, 2000; Nicholls et al., 1999) as accordingly we would expect higher accuracy and/or faster responses for targets located on the left. The majority of prior studies suggest that the preferential activation of the right ventral frontoparietal network, consisting of temporo-parietal junction (TPJ) and ventral frontal cortex, underlies target detection and attentional orienting, and constitutes the neural basis of pseudoneglect and neglect (e.g., Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2011; Fox, Corbetta, Snyder, Vincent, & Raichle, 2006; Kincade, Abrams, Astafiev, Shulman, & Corbetta, 2005; Shulman et al., 2010; Vossel, Thiel, & Fink, 2006). By contrast, some recent studies have proposed that the left frontoparietal network, in particular the TPJ, is involved in attentional orienting driven by non-spatial features and that the left TPJ integrates top-down and bottom-up processes in guiding attention (DiQuattro & Geng, 2011; Hodsoll, Mevorach, & Humphreys, 2009; Mevorach, Humphreys, & Shalev, 2006b; Weidner, Krummenacher, Reimann, Muller, & Fink, 2009). Our findings seem to be consistent with these reports and with the idea that the left and not the right frontoparietal network guides attention

based on non-spatial features with contextual relevance (see Geng & Vossel, 2013 for further evidence and discussion).

The most striking finding of the current study is the observed polarity and target location dependent effect of tDCS on the accuracy of target detection. Specifically, we showed that bi-parietal tDCS affected the detection of targets located within the left but not the right hemi-filed, and only targets accompanied by perceptually similar distractors. Furthermore, the effects of stimulation were polarity specific, i.e., the LH anodal/RH cathodal stimulation significantly decreased the detection accuracy of left targets presented with similar distractors as opposed to the sham and the RH anodal/LH cathodal stimulation conditions. It should be noted that Bayesian analyses also provided moderate evidence suggesting distinct effects of LH anodal/RH cathodal versus RH anodal/LH stimulation on detection accuracy of left targets accompanied by perceptually salient distractors. But taking into account the results of other reported tests this finding should be considered with caution.

Taking into account the relatively low spatial selectivity (resolution) of the employed tDCS protocol, we cannot separate the effects of the stimulation on discrete neural substrates of attention within either the dorsal or the ventral frontoparietal networks. Consequently, it is very improbable that the stimulation uniquely targeted a single attentional process. Based on the functional organization of the neural networks sub-serving visual attention (Corbetta & Shulman, 2002), the employed here bi-parietal tDCS likely affected multiple attentional mechanisms, including the interplay between top-down and bottom-up processes as well as interhemispheric balance mechanisms controlling the spatial allocation of visual attention. Therefore, the reported findings could be understood in terms of simultaneous modulation of these separate aspects of visual attention.

It is generally assumed that the effects of tDCS result from changes in cortical excitability, and that tDCS triggers differential outcomes in a polarity dependent manner, with the anodal stimulation increasing, while the cathodal stimulation decreasing cortical excitability, resulting in facilitation

and inhibition of cognitive processes, respectively (Nitsche et al., 2008; Nitsche & Paulus, 2000, 2001). While this striking dichotomy in the polarity dependent effects of tDCS has been quite consistently replicated in the motor system (Nitsche et al., 2008; Nitsche & Paulus, 2000, 2001; O'Shea et al., 2014; Stagg & Nitsche, 2011), the findings reported in studies examining the effects of tDCS on visual attention are often contradictory and the effects seem to be highly dependent on the stimulation site (i.e., left versus right hemisphere; Benwell et al., 2015; Bolognini et al., 2010; Filmer et al., 2015; Giglia et al., 2011; Moos et al., 2012; Roy et al., 2015; Sparing et al., 2009; Weiss & Lavidor, 2012; Wright & Krekelberg, 2014). Some studies have indeed shown that anodal tDCS, applied over the PPC, seems to improve attentional functions, similarly to tDCS modulation observed for other cognitive domains; (e.g., Cerruti & Schlaug, 2009; Chi, Fregni, & Snyder, 2010; Roy et al., 2015; Sparing et al., 2009 ; although see Filmer et al., 2015 for opposite effects). By contrast, the cathodal stimulation (applied over the PPC) has been shown to either deteriorate or enhance performance in tasks measuring visual attention functions (e.g., Giglia et al., 2011 versus Moos et al., 2012; Weiss & Lavidor, 2012). However, while both Moos et al. (2012) and Giglia et al. (2011) employed tDCS applied over the right PPC, the first study reported the tDCS-induced enhancement of the top-down control of attention, whereas the latter measured the effects of stimulation on the interhemispheric balance and the shift in the spatial allocation of visual attention. Furthermore, it should be noted that the effects of tDCS on attention have been frequently observed only when stimulation is applied to the right but not the left hemisphere (e.g., Filmer et al., 2015; Roy et al., 2015). Interestingly, Filmer et al. (2015) demonstrated that regardless of the stimulation polarity, tCDS applied over the right PPC disrupted detection of competing stimuli, simultaneously presented within the left and the right visual hemi-fields. Finally, Giglia et al. (2011) also showed that while bi-parietal tDCS (i.e., right cathodal and left anodal tDCS), similarly to unilateral right cathodal tDCS resulted in a rightward spatial bias of attention, the effects of bilateral stimulation were significantly stronger compared to unilateral stimulation (see also O'Shea

et al., 2014 for contradictory findings concerning the effects of unilateral versus bilateral stimulation). Taking together all prior evidence and our findings, we suggest that overall bilateral tDCS stimulation regardless of polarity seems to exert stronger effects on the attentional control compared to the effects on the shift (lateralization) in the allocation of visual attention. Subsequently, we suggest that LH anodal/RH cathodal stimulation significantly decreased accuracy of detecting left targets accompanied by contralateral similar distractors because this stimulation resulted in both a rightward shift in the allocation of visual attention (i.e. towards distractor) and an increased bottom-up control enhancing attentional capture by the similar distractor in the right visual hemi-field. In contrast, LH anodal/RH cathodal stimulation had no significant effect on the accuracy of detecting left targets accompanied by contralateral salient distractors, because, while this stimulation resulted in both a rightward shift in the allocation of visual attention and an increased bottom-up capture by salient distractor, the latter likely resulted in an enhanced distractor rejection causing a rapid reorientation of attention towards the left targets and thus having an opposite effect with respect to the rightward spatial shift. Furthermore, LH anodal/RH cathodal stimulation had no significant effects on the accuracy of detecting the right targets accompanied by contralateral either similar or salient distractors due to likely opposite effects on an increased bottom-up capture and the rightward shift in the allocation of visual attention, with the former being a significantly stronger effect. Finally, we suggest that RH anodal/LH cathodal stimulation significantly increased accuracy of detecting the left targets accompanied by contralateral similar distractors because this stimulation resulted in both a weak leftward shift in the allocation of visual attention and a decreased bottom-up control, lessening attentional capture by the similar distractor in the right visual hemi-field. We also suggest that overall both anodal and cathodal tDCS stimulation seems to exerts stronger effects on the bottom-up control compared to the effects on the shift in the allocation of visual attention. However, an alternative explanation of the reported findings could be proposed. It could be suggested that the findings are in line with an

overall tDCS effect on distractor suppression in conditions of high competition (i.e., target presented with similar distracter). Such an effect could be explained by a field-specific impact of tDCS on attentional priority of the target, which manifests only in conditions of high similarity between target and distractor.

Overall, the accuracy results suggest that LH anodal/RH cathodal stimulation had a detrimental effect on performance when the target was on the left and the distractor was similar. This result might indicate that left parietal excitation (and right parietal inhibition) impairs detection of targets in the left visual field, especially when there is a strong distractor competition. Why such effects were observed only for left targets under the condition of the left parietal excitation/right parietal inhibition, and not for right targets under the condition of the right parietal excitation/left parietal inhibition is unclear. Perhaps the explanation lies in the combined hemispheric specific and polarity specific effects of bi-parietal stimulation. However, as stated above prior studies examining the effects of either unilateral or bilateral tDCS on visual attention provided contradictory evidence with regards to stimulation site (left versus right hemisphere) and polarity (anodal versus cathodal) and thus any interpretation would not be straightforward.

In addition to assessing the effects of bi-parietal tDCS on the accuracy of target detection, we also measured tDCS-induced changes in speed of performance (RTs). Prior studies examining the effects of tDCS on visual attention as measured by changes in RTs are largely inconsistent, with some reporting polarity-dependent (anodal versus cathodal) or stimulus location-dependent (with respect to stimulation site i.e., ipsilateral or contralateral hemi-field) effects, while others reporting no effects or effects independent of stimulation type/polarity (e.g., Filmer et al., 2015; Li et al., 2015; Medina et al., 2013; Roy et al., 2015; Sparing et al., 2009; Weiss & Lavidor, 2012). Thus, the presented in the current study findings that the effects of stimulation on RT were not polarity dependent are in agreement with some prior reports. Specifically, we found that both bi-parietal RH anodal/LH cathodal and LH anodal/RH cathodal tDCS (but not sham stimulation) had

detrimental effects on the speed of target detection. While there was an overall effect of practice (participants were faster in correctly detecting targets when performing the task for the second time during each session i.e., during tDCS or sham stimulation, compared to baseline), but this increase in speed of performance was significantly smaller when either RH anodal/LH cathodal or LH anodal/RH cathodal tDCS were applied compared to sham stimulation. This suggests detrimental effect of bi-parietal tDCS regardless of its polarity. Although, it should be noted that a subsequent analyses based on Bayesian t-tests provided only weak evidence that RH anodal/LH cathodal stimulation had a significant effect compared to sham stimulation and only when the target was presented with a similar distractor. By contrast, some prior studies reported that uni-parietal anodal tDCS speeded response times in visual attention tasks (e.g., Bolognini et al., 2010; Roy et al., 2015; Sparing et al., 2009). But while such effects (i.e., faster RTs) could be triggered regardless of whether anodal tDCS was applied over the left or the right PPC, the stimulation differentially affected the detection of stimuli presented unilaterally versus bilaterally (slower versus faster response times, respectively; see Sparing et al., 2009). In the present study, we assessed attentional selection using a paradigm in which a lateralized (left or right visual hemi-field) target was presented alone or together with a contralateral, similar or salient, distractor. It is thus plausible that bi-parietal and bidirectional (RH anodal/LH cathodal or LH anodal/RH cathodal) tDCS simultaneously affected the interplay between bottom-up and top-down processes in attentional selection, and the interhemispheric competition mechanisms allocating attention to the contralateral versus the ipsilateral hemi-filed (Heilman & Van Den Abell, 1980; Kinsbourne, 1987, 1993). Thus, bi-parietal tDCS resulted in detrimental rather than beneficial effects on response times regardless of polarity.

The fact that the application of bi-parietal tDCS resulted in polarity specific effect on the accuracy but not on the RT requires further consideration. Our ability to interpret the effects of stimulation on the RT versus the accuracy is significantly hampered by the fact that most studies only report

either the RT or the accuracy data. Nevertheless, there are two tDCS studies of potential relevance. First, in addition to testing healthy controls, Sparing and colleagues (Sparing et al., 2009) also examined the effects of stimulation on visual neglect symptoms in a small group of stroke patients (n=10). Taking into account a relatively small number of neglect patients and a large variability in response to stimulation, not surprisingly no statistically significant changes in visual attention task (from the Tests of Attentional Performance, the TAP battery) were observed. Nevertheless, Sparing et al. (2009) reported two interesting trends: (i) when active tDCS, regardless of polarity, was applied over either the intact or the damaged hemisphere, patients responded faster compared to the application of sham stimulation; (ii) cathodal tDCS applied over the intact hemisphere tended to increase, while anodal tCDS applied over the intact hemisphere tended to decrease the number of stimuli detected by patients compared to sham stimulation. Therefore, similar to our findings, there was a stimulation specific effect on accuracy, but only a generic one on RT. A second study by Li and colleagues (Li et al., 2015) examined the effects of bi-parietal tDCS on accuracy and RT in performance on CRT (choice reaction task). Interestingly, Li et al. (2015) reported that there were no effects of stimulation on accuracy (CRT error rate) but found distinct effects on vigilance (measured by change in RT) depending on polarity of bi-parietal tDCS (improvement versus decrement in vigilance level; although the actual ANOVA only showed borderline significance). Thus, both studies report a discrepancy between accuracy and RT results, in line with our findings. These studies and our own results that stimulation produces different patterns of results on RT and accuracy are also in agreement with the notion that accuracy and RT might operate via different cognitive and neural processes (see Mulder & van Maanen, 2013; Prinzmetal, McCool, & Park, 2005; van Ede, de Lange, & Maris, 2012). It is commonly assumed that results for both the accuracy and the RT should produce the same interpretation (e.g., faster and more accurate responses both indicate better performance) and reflect the same underlying mechanisms. However, a recent study by van Ede and colleagues (van Ede et al., 2012) using a cued somatosensory discrimination

task and measuring both behavioural performance and magnetoencephalography, elegantly demonstrated that the accuracy and RT are affected by an attentional cue via distinct cognitive and neural processes underlying the decision reflected by the recorded responses.

Final remarks and conclusions. The presented here findings suggest that bi-parietal tDCS can modulate some, but not all, aspects of the interplay between task-driven and stimulus-driven attentional selection in a polarity-dependent manner, as indicated by the differential tDCS effects on RTs and accuracy in task performance. Specifically, we have shown polarity and target location dependent effects of tDCS on accuracy, but not RTs, in the detection of targets presented with similar distractors. Due to the low spatial resolution of the applied tDCS technique (also commonly used in other studies; see for example Benwell et al., 2015; Bolognini et al., 2010; Filmer et al., 2015; Giglia et al., 2011; Moos et al., 2012; Roy et al., 2015; Sparing et al., 2009; Weiss & Lavidor, 2012; Wright & Krekelberg, 2014), it was impossible to specifically target distinct cortical regions controlling different attentional mechanisms. Based on prior evidence we suggest that the polarity and target location dependent effects of bi-parietal tDCS on the accuracy of detection of targets presented with a similar distractor, resulted from simultaneous modulation of the interaction between top-down and bottom-up processes and the interhemispheric competition mechanisms guiding the attentional selection and spatial allocation of visual attention. Similar to prior studies our findings indicate that the effects of tDCS applied over the PPC on visual attention vary depending on stimulation polarity, However, our data also indicate that the polarity of the applied stimulation might have opposite effects on different attentional mechanism. Thus, we conclude that not only the interpretation of the results, but also the clinical application of this type of stimulation as a potential approach for the rehabilitation of visual attention deficits, requires careful consideration of the potentially differential effects on distinct attentional functions.

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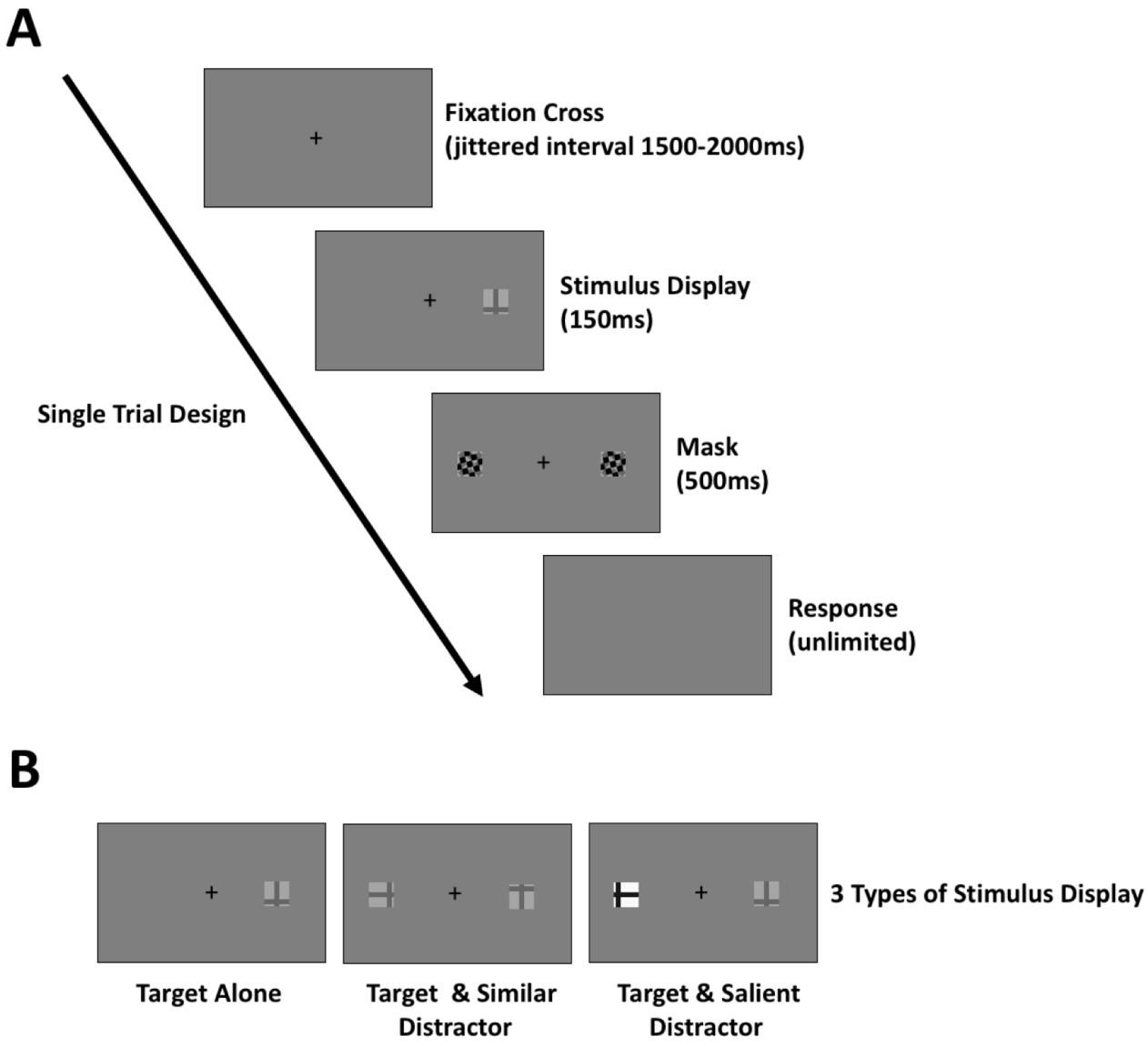
FIGURE LEGENDS

Figure 1. Visual Target Discrimination Task: (A) Each trial began with a fixation cross followed by a stimulus display, which was subsequently masked. Participants were asked to respond to target orientation i.e., upright or inverted " † "(modified from Geng & DiQuattro, 2010). **(B)** Examples of stimulus display: target alone, target & similar distractor, target & salient distractor. The target was presented randomly either within the left or the right visual hemi-field.

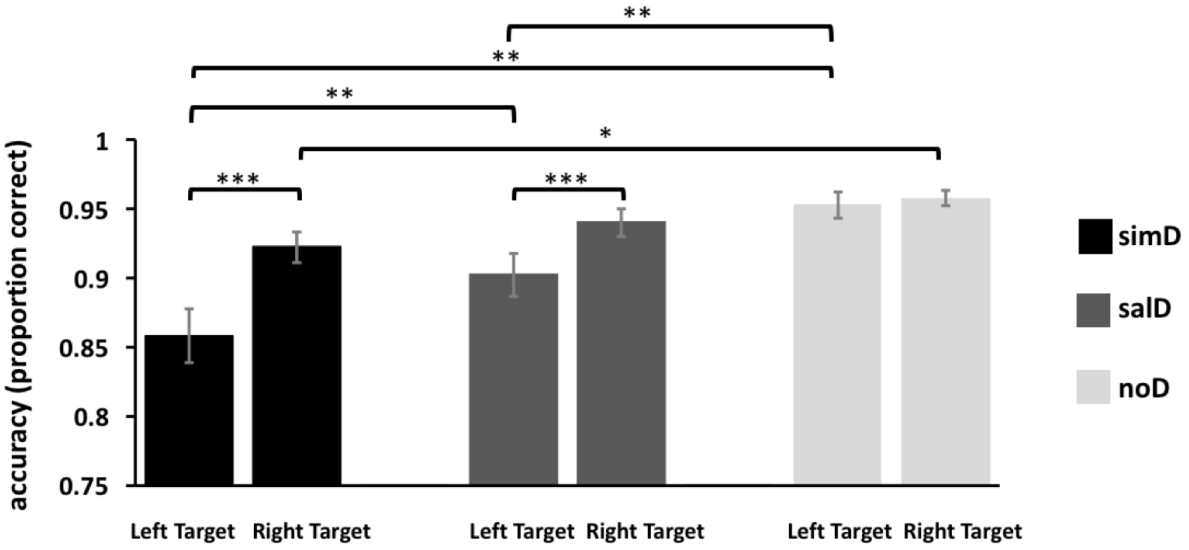
Figure 2. Baseline accuracy **(A)** and RTs **(B)** of target detection for each type of stimulus display. simD, similar distractor condition; salD, salient distractor condition; noD, no distractor condition; *p<0.01, **p<0.001, ** p<0.0005 significant post-hoc pairwise comparisons after Bonferroni correction.

Figure 3. Effects of tDCS (difference in performance during stimulation minus pre stimulation i.e., at baseline) on the accuracy of (A) left and (B) right target detection, plotted for each type of distractor. Positive values indicate higher accuracy during stimulation compared to baseline; and negative values indicate lower accuracy during stimulation than baseline. simD, similar distractor condition; salD, salient distractor condition; noD, no distractor condition; * p<0.0001 significant post-hoc pairwise comparisons after Bonferroni correction.

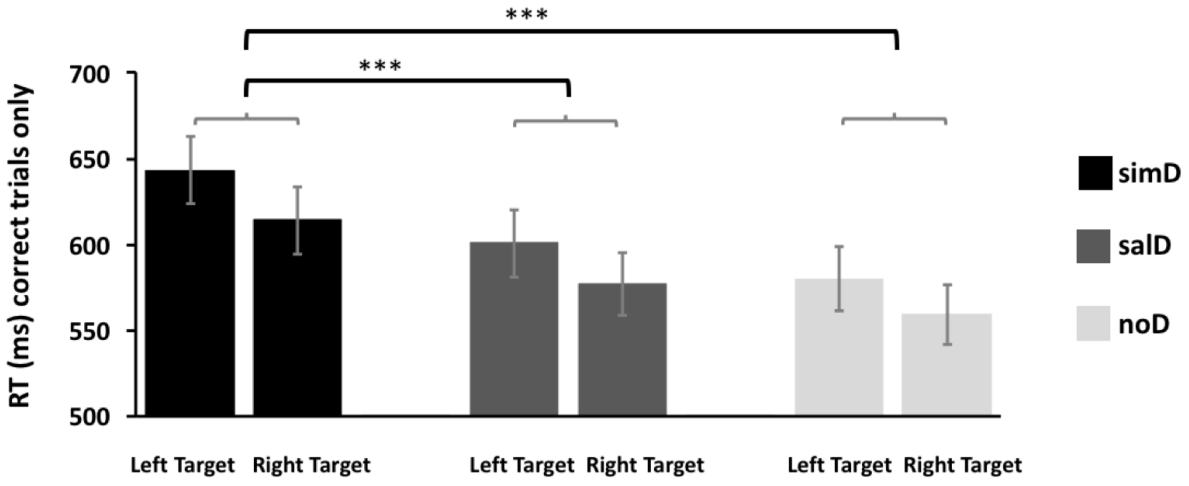
Figure 4. Effects of tDCS (difference in performance during stimulation minus pre stimulation i.e., at baseline) on the RTs of target detection plotted for each type of distractor (collapsed across target location). The larger negative value plotted here, the faster performance during the stimulation compared to baseline. simD, similar distractor condition; salD, salient distractor condition; noD, no distractor condition; * p<0.0001 significant post-hoc pairwise comparisons after Bonferroni correction.

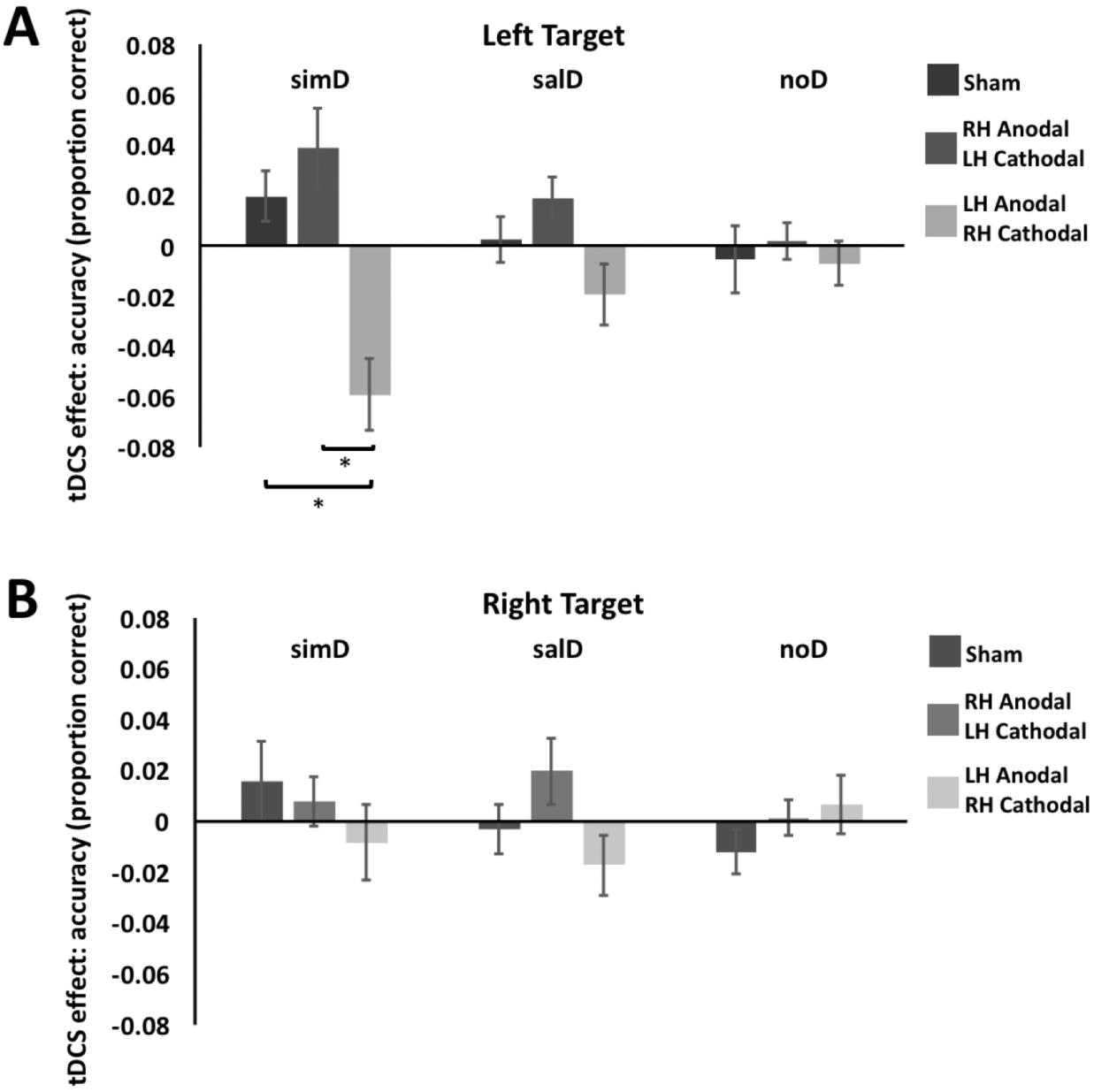

A
Fixation Cross
(jittered interval 1500-2000ms)
Stimulus Display
(150ms)
Single Trial Design
Mask
(500ms)
Response
(unlimited)
B
3 Types of Stimulus Display
Target Alone
Target & Similar
Distractor
Target & Salient
Distractor

A


**
**
**
*
***
***
accuracy (proportion correct)
1
0.95
0.9
0.85
0.8
0.75
Left Target
Right Target
Left Target
Right Target
Left Target
Right Target
simD
salD
noD

B


***
***
RT (ms) correct trials only
700
650
600
550
500
Left Target
Right Target
Left Target
Right Target
Left Target
Right Target
simD
salD
noD


A
Left Target
tDCS effect: accuracy (proportion correct)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
simD
salD
noD
*
*
Sham
RH Anodal
LH Cathodal
LH Anodal
RH Cathodal
B
Right Target
tDCS effect: accuracy (proportion correct)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
simD
salD
noD
Sham
RH Anodal
LH Cathodal
LH Anodal
RH Cathodal

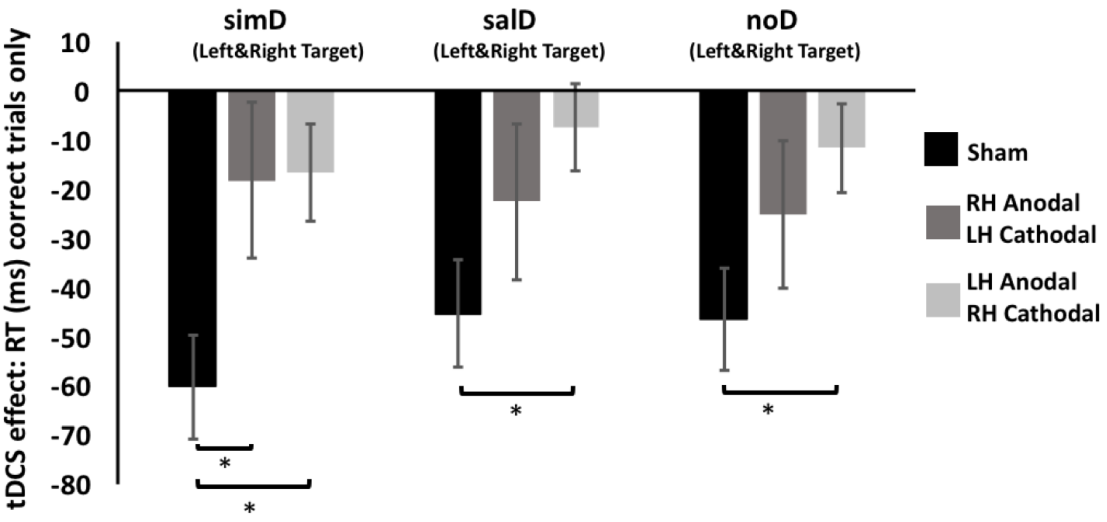

simD
(Left&Right Target)
salD
(Left&Right Target)
noD
(Left&Right Target)
tDCS effect: RT (ms) correct trials only
10
0
-10
-20
-30
-40
-50
-60
-70
-80
*
*
*
*
Sham
RH Anodal
LH Cathodal
LH Anodal
RH Cathodal

Table 1. Bayesian Paired Samples T-Tests comparing the effects of stimulation on the accuracy of target detection

			BF_{10}	Error %
Left Target				
	simD			
Sham	versus	RHanodal/LHcathodal	0.345	0.024
Sham	versus	LHanodal/RHcathodal	**86.249**	<0.00001
RHanodal/LHcathodal	versus	LHanodal/RHcathodal	**100.208**	<0.00001
	salD			
Sham	versus	RHanodal/LHcathodal	0.496	0.016
Sham	versus	LHanodal/RHcathodal	0.540	0.014
RHanodal/LHcathodal	versus	LHanodal/RHcathodal	**5.398**	0.002
Right Target				
	simD			
Sham	versus	RHanodal/LHcathodal	0.242	0.027
Sham	versus	LHanodal/RHcathodal	0.357	0.024
RHanodal/LHcathodal	versus	LHanodal/RHcathodal	0.346	0.024
	salD			
Sham	versus	RHanodal/LHcathodal	0.544	0.014
Sham	versus	LHanodal/RHcathodal	0.282	0.027
RHanodal/LHcathodal	versus	LHanodal/RHcathodal	1.543	<0.00001

simD, similar distractor condition; salD, salient distractor condition; noD, no distractor condition;

Table 2. Bayesian Paired Samples T-Tests comparing the effects of stimulation on the RTs of target detection

			BF_{10}	Error %
	simD			
Sham	versus	RHanodal/LHcathodal	1.449	<0.00001
Sham	versus	LHanodal/RHcathodal	**5.173**	0.002
RHanodal/LHcathodal	versus	LHanodal/RHcathodal	0.228	0.027
	salD			
Sham	versus	RHanodal/LHcathodal	0.375	0.023
Sham	versus	LHanodal/RHcathodal	**4.223**	0.002
RHanodal/LHcathodal	versus	LHanodal/RHcathodal	0.314	0.026
	noD			
Sham	versus	RHanodal/LHcathodal	0.370	0.023
Sham	versus	LHanodal/RHcathodal	**3.942**	0.002
RHanodal/LHcathodal	versus	LHanodal/RHcathodal	0.290	0.026

simD, similar distractor condition; salD, salient distractor condition; noD, no distractor condition;